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DYNAMICS OF SMALL AND LARGE SCALE IRREGULARITIES AT
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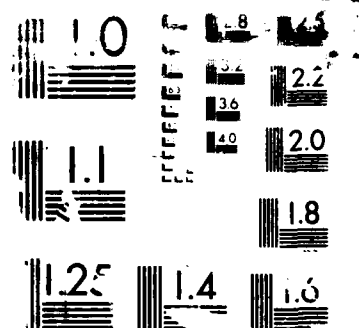
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FINAL REPORT

Covering the period: May 1, 1985-August 31, 1987

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Jules Aarons and Michael Mendillo, Co-Principal Investigators

Scientific Program Officer: R. G. Joiner, ONR

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Boston University
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TABLE OF CONTENTS

I. RESEARCH OBJECTIVES

II. THE RESEARCH PROGRAM

III. RESEARCH STUDIES

A. F-LAYER IRREGULARITY OBSERVATIONS OF THE SAR ARC

EVENT OF MARCH 5-6, 1981

B. COORDINATION WITH MILLSTONE HILL OBSERVATIONS

C. CONJUGATE POINT STUDIES OF IONOSPHERIC F-LAYER IRREGULARITIES

D. PLASMAPAUSE IRREGULARITIES IN THE F LAYER AND LOW ENERGY

(<12 eV) ELECTRON PRECIPITATION

IV. CONCLUSIONS AND FUTURE STUDIES

V. PUBLICATION SUMMARY

I. RESEARCH OBJECTIVES

The aim of the contract was to study the dynamics of ionospheric irregularities at latitudes below the auroral oval with concentration on sub-auroral mechanisms and morphology. These irregularities at altitudes of 200-500 km affect high frequency communications and radar transmissions. In HF communications, rapid fading is experienced during periods of intense irregularities; in long range HF detection, fading is experienced and the irregularities act as false targets with relatively high velocities. On satellite signals the irregularities at sub-auroral latitudes produce moderate fading at 250 MHz but fading up to 20 dB at 136 MHz.

The studies of the Boston University group encompass radio, optical, incoherent scatter and in-situ satellite data. Direct observations of the irregularities using the Mobile Ionospheric Observatory are made by BU personnel. Other observations including incoherent scatter observations from the Millstone Hill Radar are also available.

As outlined in our proposal we expected to:

- (1) organize a series of measurements of sub-auroral experiments both in-house and in collaboration with available observatories. The in-house observations were to be optical measurements of sub-auroral and auroral emissions.
- (2) utilize available earlier observations to investigate the physics of the origin of sub-auroral F-layer irregularities.

The aim of the study was to find the origin of F-layer irregularities at sub-auroral latitudes near the plasmapause. This includes geomagnetic latitudes from 48° - 57° . In the U.S. that would include a large region since Washington is at 53° , Boston at 57° etc. These irregularities certainly

would be encountered in OTH scattering and in HF transmissions. It should be noted that sub-auroral irregularities at their maximum intensity are not nearly as intense as those in the auroral region during magnetic storms. However they have peak to peak fluctuations of 20 dB at 137 MHz and 6 dB at 250 MHz (auroral scintillations can reach 28 dB at 250 MHz).

II. THE RESEARCH PROGRAM

Considerable progress was made in the research effort during the first year. Initially in this contract a great deal of study went into gathering the observations, reducing the records, and studying the relationships of the large set of observations. The progress that resulted was twofold: The data base was expanded with most of the older and new observations reduced. The second was that the principal investigators have come to two main conclusions i.e. (1) the mid-latitude ionospheric observations could be understood by ordering them in step with the time development of the ring current during a magnetic storm (2) the weaker Stable Auroral Red Arcs (SAR Arcs) detected in our recent experiments are important in determining the physics of the generation of these red line emissions. In both cases the energy conversion from ring current ion densities into ion-cyclotron waves and then into low energy electron precipitation must be studied more in detail. The understanding of the phenomena is the first step in being able to forecast and predict ionospheric effects on radio propagation in the region from High Frequency to Very High Frequencies.

Several studies were pursued; these are in various stages of completion.

III. RESEARCH STUDIES

A. F-LAYER IRREGULARITY OBSERVATIONS OF THE SAR ARC EVENT OF MARCH 5-6, 1981

One study concentrated on observations in the Northeast U.S. of the Stable Auroral Red Arc of March 5-6, 1981. The SAR arc observations of Wantanabe and Kim of the State University of Albany found that the March 5-6 SAR arc was unique. It was the most intense observed during the past twelve years at Albany, N.Y. A visible aurora was not sighted from Albany, N.Y. during the observation period.

Stable auroral red arcs occurring in "middle latitudes" have been associated with F-layer irregularities by utilizing several measurement techniques. Basu (1974) established that during the post-main phase of several magnetic storms, scintillation activity was observed during the appearance of SAR arcs. One study done under this contract concentrated on observations in the Northeast U.S. of the Stable Auroral Red Arc of March 5-6, 1981.

(1) During the post recovery period, the plasmopause associated SAR arc was accompanied by intense F-layer irregularities at these latitudes. During this SAR arc, auroral latitude irregularities displayed quiet day characteristics.

(2) With the extension of studies into the entire month of March 1981 it was found that during other days, frequently clumped, plasmopause latitudes contain irregularities without being accompanied by SAR arcs as recorded by the State University of N.Y. at Albany.

(3) During the scintillation activity accompanying the SAR arc at the plasmopause latitudes, total electron content fluctuations or oscillations occurred. These were due to the passage through the propagation path of either vertical columns of increased electron density from 200-600 km in altitude or to oscillations in the height of the F layer which would also produce fluctuations in the polarimeter records.

(4) Scintillation activity at plasmopause latitudes is not unique; during the month of March 1981 60% of the nights showed strong scintillations at 137 MHz lasting one hour or longer. In a perusal of similar data for August 1984 activity is again present on many nights.

This study was completed with results showing the high occurrence of irregularities during the recovery phase of magnetic storms as well as considerable scintillation activity in the aftermath of some magnetic storms. A paper with the title "F Layer Irregularity Observations of the SAR Arc Events of March 5-6, 1981" was published in the January 1987 issue of Radio Science.

B. MILLSTONE HILL OBSERVATIONS

The largest effort has been placed in the study of parameters obtained during three periods of time when intensive measurements were made in the sub-auroral region near Boston. These are the periods of November 9-14, 1983, September 17-24, 1984 and April 21-23, 1985. Optical observations of the Boston University Mobile Ionospheric Observatory and radio scintillations recordings were accompanied by intensive operations of the Millstone Hill Ionospheric Radar.

The gridding of the data for the April and November periods has been completed. The reduction of the data for the November period is proceeding. A paper has been completed on the observations of April 21-23, 1985 and has been published in the Proceedings of the Satellite Beacon Symposium (1986). A more complete paper on the integration of the November and April data sets given at the URSI Symposium on Large Scale Structures in Boulder, Col. in December, 1986 will be published in the Annales Geophysicae A.

The availability of coordinated Millstone Hill electron density profiles and Mobile Ionospheric Observatory images of 6300 Å emission make possible computer model checks of self-consistency between these two data sets. A versatile code has been developed that computes the 6300 Å levels produced by F region recombination chemistry and the SAR emissions resulting from enhanced electron temperatures in the F region. By comparing these computations with the various structures in an image (mid-latitude airglow, SAR arcs, diffuse aurora) we can estimate the geophysical sources contributing to the visible features (e.g. chemical recombination, heat conduction, low energy precipitating particle fluxes). Preliminary use of the code is described in the Annales Geophysicae paper.

The period of September 17-24, 1984 has a plethora of geophysical conditions including very quiet periods as well as magnetic storms. The Millstone Hill Ionospheric Radar was on the air with meridian scans for 24 hours for each day. The Millstone parameters being obtained through the use of the Boston University data processing color graphics allow the plotting of electron temperature, electron density, and ion velocity from 25°N to 60°N geographic latitudes thus encompassing the plasmopause and the auroral regions. The satellite beacon observations (6 sources) have trans-ionospheric intersections from 39° geographic to 60° geographic. The data has been reduced. Joint studies with the staff of Millstone have been started.

The concept is to see what are the necessary conditions for the development or convection of irregularities. Several hypotheses will be examined for correlation of ionospheric parameters and scintillation including that advanced for decreasing electron density and increasing electron temperature in a particular area as a source for the generation of irregularities in the auroral region. There will also be an examination of the role of shear in creating turbulence.

Some dramatic observations were made in the local area in April 1985. In collaboration with M. Kelley of Cornell a series of measurements led to the correlation of structures in the diffuse aurora at sub-auroral latitudes during one period of magnetic activity with undulations in the F region of electron density; at the same time there were high levels of satellite scintillations. This allowed for an optical signature of F-layer irregularities produced when shears in ionospheric convection were noted on the Millstone Hill Incoherent Scatter Radar. During the same April 1985 period, several hours of observations of patches of 6300Å emission were

noted in the trough region. These features waxed and waned, merged and reappeared, but never formed a unified SAR type of pattern. Observations from Millstone Hill and our 6300 A generation code were used to investigate the thermal versus particle-induced sources of the emission. The first draft of a paper to be submitted to JGR reporting on both the ripples and patches is nearly completed.

Optical observations are being taken on a long term basis at Millstone Hill with semi-remote control. Scintillation and ionosonde data are obtainable for the periods when Millstone Hill was running for specific and lengthy campaigns. Several periods are now available when SAR arcs and other events occurred; these data are being reduced for specific periods.

C. CONJUGATE POINT STUDIES OF IONOSPHERIC F-LAYER IRREGULARITIES

The lines of force of the earth's magnetic field convey effects from the ionosphere of one hemisphere to the other. The original intent of this study was to determine the similarities and differences of ionospheric irregularities at F-layer heights (300-500 km) at two points, one in the Argentine Islands in the southern hemisphere and the second an ionospheric propagation point near Washington, D.C. Both sites are at times at the edge of the plasmasphere, the plasmopause. A. S. Rodger of the British Antarctic Survey has reported on conjugate point effects at the edge of the region where the earth's magnetic lines of force are connected; J. Aarons has studied irregularities in the Northern Hemisphere at similar latitudes.

The study correlated ionosoundings of spread F conditions at Argentine Island with scintillation measurements of F-layer irregularities, the latter data taken in the vicinity of Boston. Using corrected geomagnetic coordinates the two sites are within 6° of geographic longitude and 4° of latitude of being conjugate. Three sets of data have been reduced for this comparison. The dates selected were March, May, and October 1981. These are data taken in a year of high solar flux with a great deal of in-situ observations available, particularly those from DE-2. The data set exhibited excellent correlations in the month of May 1981. The May records indicated 24 days of correlated behavior at the two sites. There were however 7 days when there was scintillation activity and little spread F. The October data set revealed 18 days of good correlation but with 10 days of some spread F and little scintillation. A paper written by Rodger and Aarons has been accepted by the Journal of Atmospheric and Terrestrial Physics.

The data set and methods of graphing led to an important further study. The appearance of intense irregularities at both stations was confined to specific period in general. When the parameter Dst was correlated with the irregularity data there were similarities noted in the temporal pattern. This led to the studies outlined in Section E.

D. PLASMAPAUSE IRREGULARITIES IN THE F LAYER AND LOW ENERGY (<12 eV) ELECTRON PRECIPITATION

Using the same group of observing stations in Northeast U.S., as on the study of the March 5/6, 1981 events, a comparison was made between in-situ observations of low energy electron precipitation (<12 eV) with the DE-2 satellite and scintillations. C. Gurgiolo of the Southwest Research Institute collaborated on this study.

For the period Sept. 22-Nov. 16, 1981, correlation of low energy electron precipitation and F-layer irregularities at a latitude of 53° Corrected Geomagnetic Latitude have been obtained. When precipitation encompassed the latitude and longitude of the propagation intersection of the satellite beacon scintillation, strong scintillation (20 dB at 137 MHz) was observed on the same nights. On nights when precipitation was at latitudes considerably higher than the propagation path, either very low level scintillation activity or none at all was noted. The soft electron precipitation was accompanied by enhanced electron temperatures as has been noted earlier. This leads to possibilities of temperature related instabilities. Convection of the irregularities plays an important role when the precipitation is within 2° of the propagation path.

E. THE RING CURRENT AND SUB-AURORAL F-LAYER IRREGULARITIES

Probably the most significant advance that has been made in this period is to organize the data and separate the observations into those taking place during various stages of major magnetic storms. Thus F-layer irregularities appear during the developing phases of magnetic storms when the electric field has an important role and during the recovery phases of magnetic storms when the ring current energies have a role. This approach has changed the organization of the continuing studies.

A paper has been completed on the association of ring current energies and sub-auroral F-layer irregularities. This work is essentially a beginning to forecasting F-layer irregularities in this latitude region.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

At the sub-auroral latitudes there had been statistical correlations attempted with Kp which is a real time parameter (including some made by the Principal Investigators) but they revealed contradictory results. It is clear that at auroral latitudes magnetic deviations (local) are the most important parameter for correlation with F region irregularities. It was not clear what the effect of magnetic activity was at sub-auroral latitudes.

The second parameter for correlation was SAR arcs. It turned out that some SAR arcs reported (for example by Frank and others for October 1981) were associated with the main phase of magnetic storms and some took place after the major phase of magnetic activity. The first study of the March 5-6, 1981 SAR arc and sub-auroral irregularity intensities indicated scintillations were correlated in detail with a very intense SAR arc during a period of magnetic quiet. This occurred a day after the main activity phase of the magnetic storm. Scintillation activity and spread F at sub-auroral latitudes therefore can take place (as do SAR arcs) during the main phase of a magnetic storm and during the recovery phase when Kp is at low or moderate levels.

This led to the next phase of the studies i.e. tying F-layer irregularities at sub-auroral latitudes with ring current energies. The magnetic field perturbation at the earth's surface is proportional to the total kinetic energy of the particle population contained in the ring current, according to Williams in several publications. The ring current magnitude is shown by Dst. Dst exhibits a major negative phase during the first part of a magnetic storm and unless another storm comes along slowly recovers. The ring current has a concentration of ion energies in the sub-

auroral region during and after the main phase of magnetic storms. It is in this area that one of the main results of the study emerged i.e. that ring current energy density is the most important source of F-layer irregularities at sub-auroral latitudes in the region of the plasmopause.

In the collaborative studies with the Southwest Research Institute and with the British Antarctic Survey we have shown that the F-layer irregularities at sub-auroral latitudes follow the same temporal pattern over a matter of days as the Dst excursions. This includes times when the ring current is depleted and little spread F is seen even at auroral latitudes. A large number of sounders and scintillation propagation paths are used in ongoing and completed studies.

What does this mean? First it means that correlation with Kp for many irregularity parameters is a good approximation for the auroral region but a poor one for sub-auroral latitudes. At sub-auroral latitudes A. Rodger and J. Aarons have shown a good correlation with the ring current parameter, Dst. There are groups still trying to use Kp for SAR arc correlations. However since the SAR arcs appear during high and during low Kp there is a huge scatter. For forecasting it does show that the best means is trying to determine the phase of the magnetic storm and predict from there.

From the point of view of applications, the approach and the results tie together distant space measurements from two to six earth radii to ionospheric parameters which are of importance in communications and detection. More measurements of ion energies at satellite altitudes from 2 to 6 earth radii could lead to better forecasting of both the positions and intensity of irregularities at F-layer altitudes.

In studying large and small scale irregularities from sounder measurements, in-situ energetic particle satellite observations,

scintillations, and SAR arc observations it became apparent that we would have to correlate sub-auroral irregularities with auroral irregularities. We would also have to look at the time development during a magnetic storm. The large magnetic storms are certainly the most troublesome periods of F-layer irregularities both at auroral and sub-auroral latitudes.

The studies have led to a serious re-assessment of the role of precipitating electrons and ions at mid-latitudes. The SAR modelling versus the observations indicates that heat conduction alone from the ring current is insufficient to account for the 6300 Å intensities. Thus precipitating electrons are an important source of small scale irregularities and elevated electron temperatures while ions may contribute to larger scale SAR patterns.

V. PUBLICATION AND PRESENTATION SUMMARY OF BOSTON UNIVERSITY PERSONNEL
SUPPORTED BY CONTRACT

A. Publications Supported Under Earlier Studies

- Aarons, J. (1985) Construction of a Model of Equatorial Scintillation Intensity, *Radio Science*, 20, 397-402.
- Aarons, J. (1985) Equatorial F Layer Irregularity Patches at Anomaly Latitudes; *J. Atmos. and Terr. Phys.*, 47, 875-883
- Mendillo, M., H. Spence, and S.T. Zalesak (1985) Airglow Signatures from Plasma Instability Model of Equatorial Plasma Depletions; *J. Atmos. and Terr. Phys.*, 47, 885-893

B. Publications Under Present Contract

- Aarons, J. (1986) General Concepts of Modern HF Communication published in Conference Proceedings of MILCOM IEEE October 1986
- Aarons, J. (1987) F Layer Irregularity Observations of the SAR Arc Events of March 5-6, 1981, *Radio Science* 22, 100-110
- Aarons, J., C. Gurgiolo, and A.S. Rodger (1987) The Effects of Magnetic Storm Phases on F-Layer Irregularities from Auroral to Equatorial Latitudes. Presentation and preprint publication in the Ionospheric Effects Symposium Washington D.C. May, 1987
- Aarons, J. and A.S. Rodger (1987) Magnetic Storm Effects on F Layer Irregularities Near the Auroral Oval. Presentation and preprint publication in the AGARD Symposium on Scattering and Propagation in Random Media. Rome, Italy May, 1987
- Mendillo, M. J. Baumgardner, J. Aarons, J. Foster, and J. Klobuchar (1987) Coordinated Optical and Radio Studies of Ionospheric Disturbances: Initial Results from Millstone Hill; in press *Annales Geophysicae A*
- Rodger, A.S. and J. Aarons (1987) Studies of Ionospheric F-Region Irregularities from Geomagnetic Mid-latitude Conjugate Regions; accepted for publication *J. Atmos. and Terr. Phys.* August, 1987

C. During the calendar year 1987, the Government Printing Office issued the Handbook of Geophysics and Space Environments. J. Aarons is the Editor of Chapter 10 "Ionospheric Radio Wave Propagation". He is the coauthor of Section 10.6 with S. Basu on "Scintillation on Trans-Ionospheric Radio Signals" and M. Mendillo wrote the review article on "Artificial Modification"

D. Invited and Contributed Presentations at Topical or Scientific/Technical Conferences

Invited presentation on World Ionosphere and Thermosphere Study (WITS): J. Aarons, "Future Studies in Ionospheric Radio Propagation" at the U.S. URSI Meeting, Boulder, CO Jan. 1986

Contributed Presentation: At the Satellite Beacon Symposium Oulu, Finland May 1986 "Coordinated Optical and Satellite Radio Beacon Studies of Ionospheric Disturbances", M. Mendillo, J. Baumgardner, J. Aarons, and J. A. Klobuchar.

Invited as Lecture Series Director, J. Aarons developed the AGARD Lecture Series on "Propagation Impact on Modern HF Communications System Design". The series was held in Belgium, France and Denmark in April 1986; the publication (AGARD LS 145) of the lectures included J. Aarons' review and introductory lectures.

A lecture and paper were prepared for the 1986 IEEE Military Communications Conference, Monterey, CA. Oct. 5-9, 1986. A paper was printed in the Conference Record "General Concepts of Modern HF Communications". J. Aarons

Contributed paper: "Imaging and Incoherent Scatter Observations of Ionospheric Disturbances" by M. Mendillo, J. Baumgardner, and J. Foster presented at the URSI Conference on Large Scale Structure in the Ionosphere and Thermosphere: Boulder, CO January 1987

Contributed Paper: "Ionospheric Storms" by M. Mendillo was presented at the AGU Meeting May 1987

E. IN PREPARATION

Aarons, J., C. Gurgiolo, and A. S. Rodger (1987) The Effects of Magnetic Storm Phases on F-Layer Irregularities Below the Auroral Oval; submitted to Radio Science

Aarons, J. and C. Gurgiolo (1987) Sub-Auroral Irregularities in the F Layer and Low Energy (<12 eV) Electron Precipitation; in preparation

Mendillo, M.J., and J. Baumgardner (1987) F Region Signatures of Detached Arcs, Ripples in the Diffuse Aurora and Patches of Emission at 6300 Å; in preparation for submission to J. Geophys. Res.

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